IS 3D PRINTED HOUSE SUSTAINABLE?

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ABSTRACT

"3D printing technology has the potential to revolutionize the way we make almost everything", so President Barack Obama recently said (Remarks by the President in the State of the Union Address, The White House, Office of the Press Secretary, 2013): the impression is that three dimensional (3D) printing is taking the world by storm in different areas.

If for objects of small dimensions, the technology is well-established, great developments are expected in the construction industry. As a matter of fact, since the beginning of 2000, with the first attempts for a large-scale 3D printing construction system, the innovators are working around automated additive manufacturing in order to print whole buildings as well as large-scale subcomponents. To date, different processes trial has started, from the printing of elements to the layer by layer construction of entire structures in a non-stop work session, starting from the foundation level and ending on the top of the roof. Even the materials trial has started: bio based plastic, mix of grinded-down rocks or sand held together with a liquid binding agent, fiber-reinforced concrete, etc.

The objective stated by different manufacturers and researchers involved is the sustainability of the built environment, in terms of economic, environmental and social benefits. But, is this innovation really sustainable? What about the environmental sustainability of these new construction processes?

The purpose of this study is to try to give an answer to this matter, through three research phases: 1. gathering and analysis of the current information on the 3D printing technology applied to construction; 2. identification and analysis of the main systems and case studies, including those with a longer experience in terms of research and experimentation (e.g., Contour Crafting and D-Shape) and the younger ones that are rapidly gaining visibility (e.g., Canal House and the Chinese system WinSun); 3. their evaluation in terms of environmental benefits and critical environmental issues.

The results obtained from each work phases, in particular the case studies analysis, leads us to think that the potential of 3D printing technology is substantial for the construction industry. If it continues to be developed, certainly it may revolutionize the construction process. However, implementing the technology will not be without its challenges.

Keywords: 3D printing, additive manufacturing, construction, sustainability.

INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing, is defined as «a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.» [1]. It derives from the field of rapid prototyping, developed during the late 1980s and 90s. The 3D printing process begins by digitally modelling a blueprint of the object that is to be printed in a design program; this one then "slices" the object into layers and sequentially sends this information to the 3D printer that constructs the object by making repeated passes, each time depositing a thin layer of material onto material previously deposited. The 3D printing fabrication has been largely adopted, with applications in several sectors (e.g., automotive, aerospace, medical), up to current commercial availability of desktop-sized devices at affordable prices. If for small objects the technology is well-established, great developments are expected in the construction industry too, not only for the creation of scale models of buildings.

The use of additive manufacturing in construction (AMC) was suggested by Pegna in the late 1990s [2]. He investigated a new system of layered fabrication of small masonry structures, involved depositing a layer of reactive material (Portland cement) over a layer of matrix material (silica), activated by water vapor. The first attempts to apply this new technology date back to early 2000, with the experiments for a large-scale combined extrusion and trowel ‘automated construction’ system called Contour Crafting [3]. Since then, the innovators have been working around automated additive manufacturing and different processes trials started: from the printing of small components to be assembled to form architectural elements (e.g., Emerging Objects [4]), to the molding of hollow honeycomb elements subsequently filled and then assembled of the Amsterdam Canal House [5] and to the possibility of a layer by layer construction of entire structures in a non-stop work session, as with the D-Shape system [6]. Even the materials trial has started: bio based plastic, mix of grinded-down rocks or sand held together with a liquid binding agent, fiber-reinforced concrete, etc.

The objective, stated by different manufacturers and researchers involved, is the sustainability of the built environment, in terms of economic, environmental and social benefits, such as the aims stated in "Houses of the future" of Khoshnevisk [7]. But, is this innovation really sustainable? How will these houses be about environmental sustainability?

The aim of this paper is the attempt to give an answer to this question, through the identification of the main, experimental case studies and the analysis in terms of environmental benefits and potential problems.

METHOD

The research was developed in three phases:

1. Gathering of information on 3D printing in construction

3D printing technology applied to construction was analysed, gathering information from sources at different levels: scientific articles, information from manufacturers, informative articles. The keywords used for searching are both words that indicate the type of process (e.g., additive manufacturing or 3D print + automated construction; construction scale + additive fabrication / manufacturing) and trade names of systems (e.g., D-Shape).

2. Identification and technical analysis of main systems

A selection was made among the identified systems, narrowing the field of investigation on the following criteria:

- systems that are all actively undergoing development, rather than systems which, although their high scientific value, have been relegated essentially to the research area (i.e. Pegna);
- systems involve the use of large machines that can print from big elements up to entire buildings, instead of machines for printing small elements such as tiles or bricks;
- systems with technical information on the process and materials, needed for the purpose of an assessment of environmental quality.

The selected systems were analysed and for each some summarized sheets were elaborated. Only the information obtained from the manufacturers and scientific articles were included in these technical sheets; the information obtained from informative articles were overlooked.

3. Assessment of environmental sustainability

An environmental sustainability evaluation was carried out for the selected systems, with remarks on the possible positive or critical issues related to the spread of AMC. Currently, data are not available for a quantitative assessment of the environmental impact of AMC, nor with regard to different aspects (emissions, energy, etc), nor for the different life cycle stages of the manufactured products.

The assessment focused on some key aspects that the producers themselves highlight as higher environmental performance compared to the traditional construction process. In particular, some aspects, related to the cycle of the materials used for printing, were assessed: from the resources to the possibility of disassembly/recycling at end of building life, without neglecting indoor environment quality aspects.

RESULTS

1. Information and sources

The state of art analysis shows a literature that consists mainly in informative articles, freely accessible from online journals. From these sources, it is possible to find information about all the different systems, even the most recent ones, such as the current experimentations in Amsterdam with the Kamer Maker system for 3D Canal House [8] or those of the Chinese firm WIN SUN [9]. The amount of information discloses the relevance of the theme and the growing interest of designers and building contractors.

A large part of the available information is disclosed on the websites of the analyzed systems. However, due to the highly experimental nature of these systems, manufacturers spread mainly general information, without going into technical details of the process and materials, even when directly questioned.

The peer reviewed scientific articles are still few, and they are mainly related to the older systems and to those most connected to research institutions, such as Contour Crafting, developed at the University of Southern California [10], Loughborough University's Freeform Construction project (UK) [11], D-Shape by Enrico Dini [12].

2. Technical analysis of selected systems

Analyzing the results of the first phase, four systems are highlighted, on which the research work is focused: Contour Crafting (CC), D-Shape (DS), Kamer Maker (KM) e Win Sun (WS).

Each of these systems involves the use of large machines that can print from large elements up to entire buildings. In addition, even if they are in experimentation from different times, all of them are leading to concrete field trials.

The selected systems have some differences in both process technology both materials used for printing. For each of these systems, a data sheet was elaborated with the main technical information on materials and processes and with the environmental performance highlighted by the producers (see example in Table 1).

<table>
<tr><th colspan="2">SYSTEM: D-SHAPE</th></tr>
<tr><th>Process</th><th>Environmental note</th></tr>
<tr><td>The system operates by straining a binder on a sand layer. An aluminium structure holds the printer head. D-Shape can print any feature that can be enveloped into a cube 6x6 meters side. The process takes place in a non-stop work session, starting from the foundation level and ending on the top of the roof. The printing rises up in sections of 5-10 mm. During the printing of each section, a ‘structural ink’ is deposited by the printer’s nozzles on the sand. Upon contact the solidification process starts and a new layer is added. The solidification process takes 24 hours to complete. Surplus sand that has not been embedded within the structure acts as a buttressing support while the solidification process takes place. This surplus sand can be reused on future buildings.
(Source: http://www.d-shape.com)</td><td rowspan="3">Transport: The aluminum structure is very light and it can be easily transported, assembled and dismantled in a few hours by two workers.

Local material: The possibility to use local sand, as zero-mile base material, makes D-shape like a technology attentive to the sustainability of the construction.

Air emissions: The used binder is an inorganic bi-component, eco-friendly; chemically, the final artificial marble is 100% environmentally friendly.

Safety: no human intervention means substantially reduced risk of accidents.
(Source: http://www.dinitech.it)</td></tr>
<tr><th>Materials</th></tr>
<tr><td>The D-shape binding chemistry exploits two inorganic reactants: the first one is a metallic oxide in powder form that is dispersed among the granular material and the powder component comprises at least one among Magnesium Oxide, Silicon Oxide, Iron Oxide, Calcium Oxide and Aluminium Oxide. The granular material is preferably selected from the group comprised of dolomite, calcareous or siliceous sands to which Magnesium Oxide is added, in a ratio set between 15% and 30% by weight. The second reactant is Magnesium Chloride ($MgCl_2$) and its various hydrates $MgCl_2(H_2O)_x$. These salts are typical ionic halides, being highly soluble in water. The hydrated Magnesium Chloride can be extracted from brine or sea water. (Cesaretti et al, 2014).</td></tr>
</table>

Table 1: D-Shape technical sheet

Comparing the printing processes of the four selected systems, two typologies were identified:

- The first (KM, CC, WS) involves the direct spillage of the print material from one or more nozzles. The print material is quick-setting. The extruded elements, if with closed section, can be filled by pouring or injection of filler material such as concrete (CC, KM).
- The second (DS) involves two print steps. During the first step, a uniform horizontal layer of granular material (sand) is deposited by the machine. During the second step, a binding liquid is sprayed on those parts of the layer which has to be bound; surplus sand that has not been embedded within the structure acts as a buttressing support while the solidification process takes place. At the end of the process, this surplus has to be removed and can be reused on future buildings.

About the printing materials, there is a strong impulse to the experimentation of different possibilities (thermoplastic materials, ceramics, cement), even within the same system:

- currently, the most used materials are agglomerates of inert materials (e.g., sand) and binding agent, with some differences between the different systems. For example, the CC system is testing concrete mix with glass or carbon fiber as reinforcement, without affecting the surface quality of printed items (since this is controlled by trowels combined to nuzzle). The DS system uses inert granular material (sand) and inorganic binders: it operates by straining a binder on a layer of granular material; the granular material is preliminarily mixed with pulverized metal oxide which reacts later with the hydrated magnesium chloride of the binding liquid. The WS systems used an agglomerate created from recycled construction waste (i.e. sand, concrete, glass fiber), industrial waste and tailings. All of these systems envisage the possibility of treating the agglomerate with additives to accelerate the hardening and thus decrease the construction time.
- The KM prints with thermoplastics. Currently, it used Macromelt, a bioplastic made of 80% of vegetable oil. Hollow elements are printed; once solidified, they can be filled with concrete.

With regard to the place of printing, at the time the WS system allows printing building components in the factory, then assembled on the construction site, instead the other systems already allow the option of printing on site.

3. Performance and critical environmental issues

The selected systems analysis highlighted the environmental aspects for which AMC would be more performing than the conventional building processes. This increased environmental sustainability is indicated by the system manufacturers.

Among the most emphasized aspects, there are those related to the printing materials, such as:

- optimization of the raw materials, with the possibility of using local materials, reused or recycled, or rapid renewable (e.g., the KM experiments with bioplastics);
- reduction/elimination of construction waste, a specific characteristic of AM technology;
- reduction of air pollutants emission, both during construction and use phase;
- easy re-use of materials and components at the end of the building life (e.g., KM defines its artifacts as «easy to be disconnected in case the house needs to be relocated» [5]).

However, some of these features are not verifiable, in particular those relating to the emissions of pollutants in the air and the materials and components re-use. Being in an area still highly experimental, the reported performances are not always supported by comprehensive technical information. This happens because the features are evolving, and the producers need to maintain confidentiality of research aspects. For example, the WS system claims to use materials mainly from recycled construction waste and treat the mixture with additives in order to speed the curing of the printing layer. However, no data are provided on the technical characteristics and on the percentage of the printing mix and the used additives. This makes it difficult to evaluate some of the environmental performances declared by the manufacturer, such as «good work environment, workers less exposed to hazardous materials and noise» or «no harm to human body, no environmental pollution» [13].

In addition to the positive aspects, the systems analysis has also highlighted some critical aspects related to the AMC. These include:

- addition of additives (not known, but presumably of chemical origin), to speed up the hardening of the mixtures, could significantly modify the indoor air quality. These additives are crucial in maintaining rapid construction time for the AMC systems, characterized by the successive deposition of layers of material with low heights, and where a new layer can be deposited when the previous one has sufficiently solidified;

- risk of emission of ultrafine particles in the air during the printing, with possible impacts on the worker health, due to the nature of the materials and the conditions in which printing is done;
- criticality, at end of life, in the disposal of thermoplastic materials, due to the percentage of polymeric materials likely present in the mixtures.

CONCLUSION

The results obtained from each of the three work phases, in particular the case studies analysis, lead us to think that the potential of 3D printing technology is substantial for the construction industry. If it continues to be developed, certainly it may revolutionize the construction process.

However, to declare the 3D construction processes as sustainable, it is necessary to have more certified information than that spread today by the producers. Some positive aspects are easy to identify as special features of the 3D construction process, such as faster and accurate construction, reduced labour costs, decreased construction waste, reduced safety risks for workers. Much further research has to be done on still unclear points such as the complete composition of the printing materials, which may have negative effects on indoor air quality in the construction and use phases and on management of demolition waste at end of life.

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